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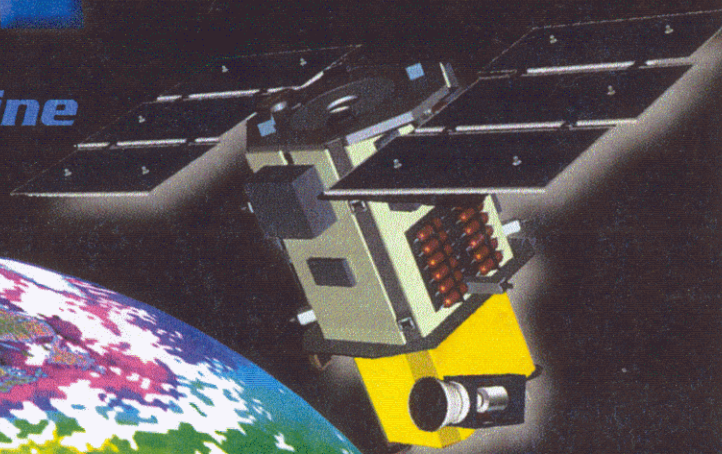
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Biospheric Monitoring and Ecological Forecasting

Ramakrishna Nemani, Michael White, Lars Pierce, Petr Votava, Joseph Coughlan, and Steve Running

The latest generation of NASA Earth Observing System (EOS) satellites has brought a new dimension to monitoring the living part of the Earth system – the biosphere. EOS data can now measure weekly global productivity of plants and ocean chlorophyll and of related biophysical factors, such as changes to land cover and to the rate of snowmelt. However, the greatest economic impact would be realized by forecasting biosphere conditions. This predictive ability would be an advanced decision-making tool used to mitigate dangers or to exploit positive trends. NASA's strategic plan for the Earth Science Enterprise (ESE) identifies ecological forecasting as a focus for future research. Ecological forecasting predicts the effects of changes in the physical, chemical, and biological environments on ecosystem state and activity. Imagine if it were possible to predict accurately shortfalls or bumper agricultural crops, or West Nile virus epidemics, or wildfire danger 3 to 6 months in advance. Such a predictive tool would allow improved preparation and logistical efficiencies.

Early knowledge of changes in key biospheric processes, such as soil moisture, snow pack, stream flow, or vegetation production, could enhance socioeconomic and natural resource management decisions. Whether preparing for the summer fire season or for spring floods, knowledge of the magnitude and direction of future conditions can save time, money, and valuable resources. Space- and ground-based observations have significantly improved the ability to monitor natural resources and to identify potential changes. However, these observations can provide information about current conditions only.

This information is useful, but many resource managers often need to make decisions 3 to 6 months in advance for the coming season. Recent advances in climate forecasting have elicited strong interest in the energy and agricultural sectors. The climate forecasting abilities of many-coupled, ocean-atmosphere, global circulation models (GCMs) have steadily improved over the past decade. Given observed anomalies in sea-surface temperatures (SSTs) from satellite data, GCMs are able to forecast general climatic conditions, including temperature and precipitation trends, 6 to 12 months into the future with reasonable accuracy.

While such climatic forecasts are useful alone, the advances in ecosystem modeling allow a specific exploration of the direct impacts of these future climate trends on the ecosystem. One-day predictions made in March might accurately forecast whether Montana's July winter wheat harvest will be greater or less than normal and whether the growing season will be early or late.

One of the key problems in adapting climate forecasts to natural ecosystems is the "memory" that these systems carry from one season to the next; for example, soil moisture, plant seed banks, or fire fuel accumulation information. Simulation models are often the best tools to carry forward this spatio-temporal memory information. The ability of models to describe and to predict ecosystem behavior has advanced dramatically over the last two decades, driven by major improvements in process-level understanding, computing technology, and the availability of a wide range of satellite- and ground-based sensors.

Terrestrial Observation and Prediction System

To estimate future states of the biosphere, researchers are building a system that integrates ecosystem models with frequent satellite observations. These models can be forced by weather or climate forecasts and can be downscaled to resolutions appropriate for resolving surface processes. Such a system would determine the vulnerabilities of different socioeconomic and resource systems to fluctuations within the biosphere and would help mitigate negative impacts. Agriculture, a $200 billion a year sector of the U.S. economy, and many other industries, such as recreation and tourism, are vulnerable to biosphere changes.

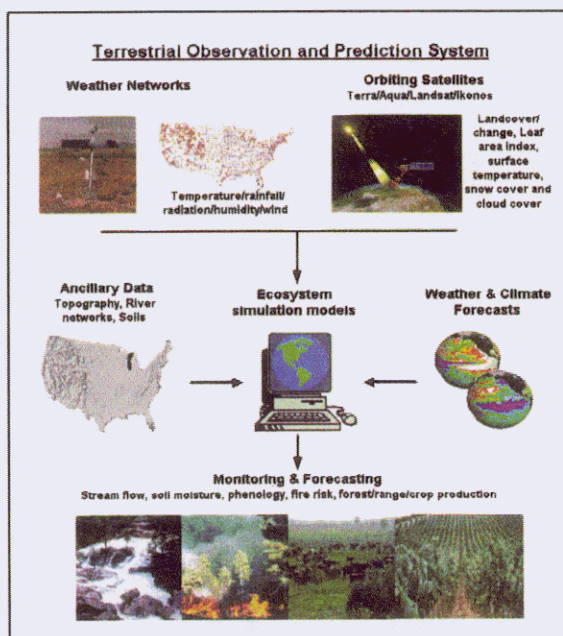Funded by NASA's Earth Science Enterprise and by the Computing, Infor-

Figure 1. The Terrestrial Observation & Prediction System (TOPS) integrates a wide variety of data sources at various space and time resolutions to produce spatially and temporally consistent input data fields, upon which ecosystem models operate to produce ecological forecasts needed by natural resource managers.

mation and Communications Technology Program of NASA's Aerospace Technology Enterprise, researchers at the University of Montana, at Utah State University, and at California State University Monterey Bay have developed a system called the Terrestrial Observation & Prediction System (TOPS) to interpret data from NASA's EOS satellites rapidly and accurately. TOPS is a modeling software system that automatically integrates and preprocesses EOS data fields so that land surface models can be run in near real time with minimal intervention. To speed the conversion of EOS data into value-added products further, TOPS automatically processes output from the models using data-mining and feature extraction tools. TOPS brings together state-of-the-art technologies in information technology, weather/climate forecasting, ecosystem modeling, and satellite remote sensing to enhance management decisions related to floods, droughts, forest fires, human health, and crop, range, and forest production (**Figure 1**).

Ecosystem Models

Spatial simulation models in ecology and hydrology estimate various water (evaporation, transpiration, stream flow, and soil water), carbon (net photosynthesis, plant growth), and nutrient flux (uptake and mineralization) processes at the landscape level. The models have been adapted for all major biomes based on each biome's unique ecophysiological adaptations to climate and soil characteristics, exploiting such biome-specific ecophysiological principles as drought resistance and cold tolerance. The models are initialized with soil physical properties and satellite-based vegetation information, such as type and density of plants.

Combined with daily weather data, these input data fields are used to simulate various ecosystem processes, such as transpiration, evaporation, photosynthesis, and snowmelt. These models are further conditioned by variations in soils, terrain, and canopy cover that can be translated into information on drought, crop yields, net primary production, and water yield estimates.

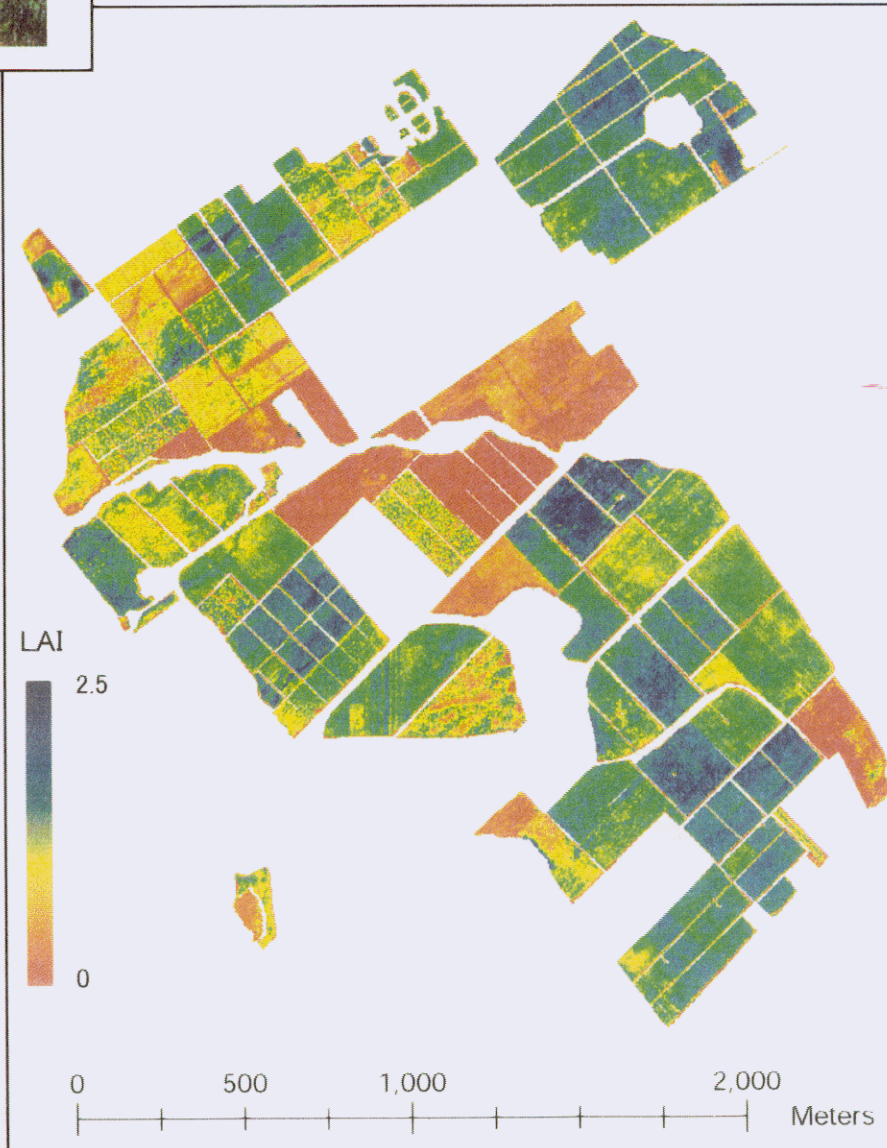A number of key developments in recent years have enabled these models

Figure 2. Maps of leaf area index derived from IKONOS satellite data collected in 2000 over vineyards in the Napa Valley, California, are important for quantifying spatial variation in canopy conditions and as inputs to ecosystem models for estimating water requirements and crop yields.

to run in nowcast and forecast modes. These developments include widespread availability of up-to-date weather conditions on the Internet, sophisticated algorithms that convert raw satellite data into various biophysical products that can be directly used in models, and operational availability of climate and weather forecasts in formats that can be used in ecosystem models.

An Ecological Forecasting Example: TOPS Helping the California Wine Industry

The impetus for developing TOPS came from NASA's research in Napa Valley, California, on the relationship between climate and wine quality and the application of remote sensing and modeling in vineyard management. Analysis of long-term climate records and wine ratings showed that interannual variability in climate has a strong impact on the yearly $30 billion California wine industry. Warmer sea surface temperatures along the California coast were found to help wine quality by modulating humidity, by reducing frost frequency, and by lengthening the growing season. Because changes in regional SSTs persist for 6 to 12 months, predicting vintage quantity and quality from previous winter conditions appears to be possible. Given the probability of an upcoming growing season to be worse or better than average, growers can use the information to make key crop management decisions.

TOPS may also help vintners during the growing season as a real-time vineyard management tool. For example, satellite remote sensing data during the early growing season helps to locate areas for pruning so that an optimum canopy density is maintained. Similarly, leaf area index (area of leaves per unit ground area) derived from satellite data is used in process models to compute water use and irrigation requirements to maintain vines at given water stress levels (**Figure 2**). Research suggests that vines need to be maintained at moderate water stress to maximize fruit quality. By integrating leaf area, soils data, and daily weather, TOPS can estimate spatially varying water requirements within the vineyard so that managers can adjust water delivery from irrigation systems (**Figure 3**). Finally, satellite imagery from the end of the growing season helps in delineating regions of similar grape maturity and quality so that differential harvesting can be employed to optimize wine blending and quality.

Additional information can be found at *www.ntsg.umt.edu/tops*.

Summary

Realizing the concept of ecological forecasting will require integrating a large number of datasets automatically and in near-real time. Advancing ecosystem science from its current state of after-the-fact studies to real time and forecasting tools would result in both economic and societal benefits. These benefits could range from reductions in climate-related agricultural losses to improved safety for people and property. Making the forecasts is just the start; properly interpreting the forecasts will be a challenging task. Success will probably require an interdisciplinary approach to properly integrate the EOS, computing, and communication technology tools necessary to achieve accurate ecological forecasts.

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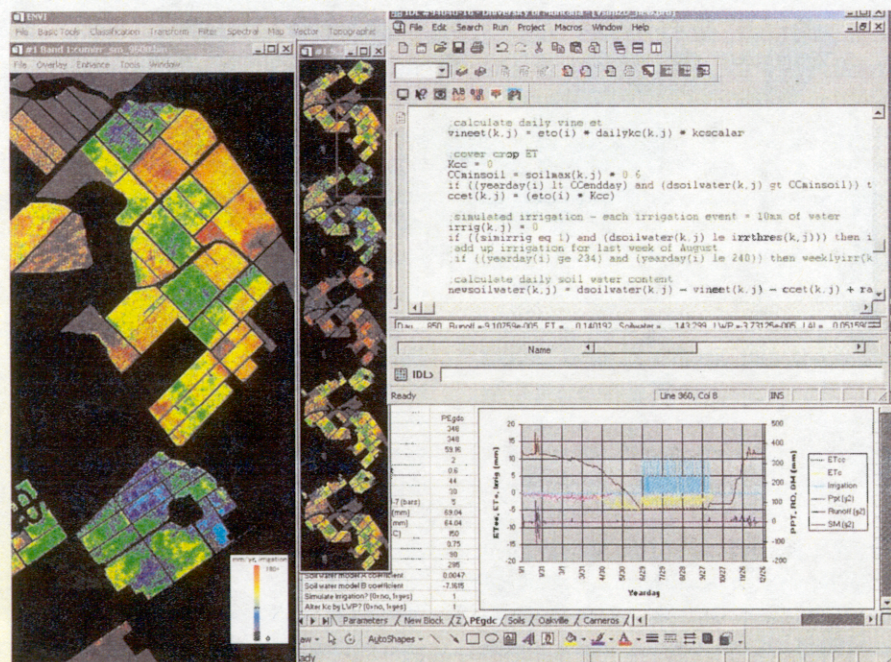

Figure 3. *TOPS combines the vineyard leaf area index maps with soils and weather data to compute a seasonal water balance that can be used to estimate the amount of irrigation required to maintain the vines at an optimal water stress level chosen to maximize crop yield and fruit quality.*